Lunar Polar Volatiles: Assessment of Existing Observations for Exploration

Executive Summary: Water is a useful resource for space exploration because it can be processed to make propellant and life-support consumables. Observations have confirmed that water ice exists on the Moon in some lunar persistently shadowed regions. Owing to the nature of instrumentation and remote sensing, nuances and assumptions are necessarily convolved with the data analysis to arrive at the published interpretations. In this white paper, we evaluate the observations related to the existence of water ice and other volatiles in the polar regions of the Moon to highlight the relative certainty of the published interpretation.

The spectral identification of water through the LCROSS impact experiment provides the strongest evidence of composition. This identification is supported by observations in the ultraviolet and the presence of H detected by neutron spectroscopy. The best evidence of the abundance of water comes from neutron spectroscopy owing to its ability to probe to depths of up to 1 m in the regolith. However the neutron spectra are not sensitive to the chemical form of H, leaving ambiguous whether the H is in the form of H_2O, hydrated minerals, or other H-bearing material. The integrated total inventory of H poleward of 80° latitude is 10^{11} kg. The physical form of the water is poorly understood. Radar data are inconsistent with pervasive, contiguous ice blocks on the size scale of >10 cm, eliminating that as a possibility. However several alternatives exist including hydrated minerals, adsorbed molecules, pore-filling ice, and small ice grains mixed with regolith. Finally, observations indicate that water ice has a heterogeneous distribution both laterally and with depth on large spatial scales. Neutron data are consistent with a desiccated layer of a few 10s of cm overlying a richer layer in most cold polar regions. Surface frost observations indicate that not all persistently shadowed regions have the same amount of frost, and that heterogeneity persists to the > 200 m spatial resolution of the data. The distribution at 1-100 m spatial scales critical for in situ resource utilization (ISRU) implementation has not been measured.

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Acronyms:

CRaTER	Cosmic Ray Telescope for the Effects of Radiation
CPR	Circular Polarization Ratio
FUV	Far Ultraviolet
ISRU	In Situ Resource Utilization
LAMP	Lyman Alpha Mapping Project
LCROSS	Lunar CRater Observation and Sensing Satellite
LEND	Lunar Energetic Neutron Detector
LIBS	Laser Induced Breakdown Spectroscopy
LOLA	Lunar Orbiter Laser Altimeter
LPNS	Lunar Prospector Neutron Spectrometer
LRO	Lunar Reconnaissance Orbiter
Mini-RF	Miniature Radio Frequency
PSR	Persistently Shadowed Region
TLS	Tunable Laser Spectroscopy

I. The importance of lunar polar volatiles

Human exploration is facilitated by ISRU because the production of consumables on site reduces the amount of material that must be launched from Earth's deep gravity well. Water is a valuable resource because it can be used to produce propellant and staples of life support. In order to conduct a feasibility study and to plan effective ISRU of lunar water, it is important to constrain the quantity, form, and distribution.

The last 15 years of exploration of the Moon has revealed that volatiles exist in lunar polar regions. Although recent results moved the state of knowledge from a hypothetical concept to an established fact, there remain unanswered questions about volatiles on the Moon. This white paper presents a summary of the current state of knowledge of volatiles on the Moon with a community-vetted evaluation of the data sets in hand. After beginning with an introduction to the exploration drivers for the topic, we address the state of knowledge regarding A) the composition, B) the distribution, C) the abundance, and D) the physical form of volatiles in the polar regions of the Moon. Finally, we offer some notes about the remaining questions of interest for Exploration.

The abundance of water is the most important constraint on the viability of the resource for use. Abundance defines the absolute limit to the availability of the desired products produced from ISRU of water. In addition, the present-day abundance is related to the original abundance and the retention efficiency, and therefore can be used to infer the inventory of volatiles in the Inner Solar System over time. Data already indicate that volatiles have a heterogeneous distribution both in depth and lateral extent. The size scale of the heterogeneity determines the amount of mobility and subsurface access needed to extract the volatiles. Relating the external conditions to the distribution will enable best application of remote sensing and reconnaissance data to predict the presence of the resource on ISRU operational scales. Understanding the processes that modify the distribution over time can indicate its stability and renewability.

At grain-size scales, the physical form of water is another variable in the distribution. There are multiple potential physical forms of water, including ice, frost, hydrated minerals, adsorbed molecules, and ice-soil mixtures. The final factor of interest is the composition, including the elemental and mineralogical constituents and isotopic ratios. The collection of constituents and isotopic data provide clues as to the original source, and therefore the renewability of the resource. Further, analysis of the composition reveals the presence of contaminants, which may be critical for designing and operating ISRU hardware systems.

Table 1. Synergy of Exploration and Science Objectives in Lunar PSRs

Quantity	**Exploration Objectives**	**Science Objectives**
Composition	Available resource	Source of volatiles
Abundance	Value, Extraction technique	Source/loss rate
Depth Distribution	Extraction technique	Age of deposits
Heterogeneity	Mobility needs	Redistribution processes

II. Current state of knowledge

A. COMPOSITION

The composition of lunar polar volatiles is determined remotely by a variety of nuclear, mass, and optical spectroscopic techniques. Spectral features can provide a “fingerprint” for the identification of both the elemental and mineralogical constituents. But spectral detection methods have limitations.

An illumination source is needed for optical reflectance spectroscopy. This is problematic in PSRs, where there is no direct sunlight. The LCROSS experiment provided the best window so far into the composition of lunar polar volatiles because the impact lofted material from the floor of a PSR into sunlight where spectra were observed. Colaprete et al. (2010) and Gladstone et al. (2010) present the spectroscopic analysis of the ejecta from the LCROSS impact into Cabeus. They identified through a combination of IR and UV spectroscopy (with $> 3\sigma$ detection) the presence of water vapor, water ice, H_2S, SO_2, OH, H_2, and CO. Figure 1 shows that adding both solid and vapor H_2O to the continuum significantly improve the model fit to the observed LCROSS spectra. An ultraviolet signature consistent with a combination of Hg, Mg, and Ca was detected. From Earth-based telescopes, Na was detected (Killen et al., 2010). However, the impact introduced some ambiguities that must be considered, especially for the minor constituents. The impact may have induced chemistry that altered the molecular composition of the material released. Although most scientists agree that water was positively detected in the LCROSS plume, identification of some of the organic species is more tentative, and the spectrum is not well-modeled longward of 2.1 μm.

Using starlight to provide illumination in the ultraviolet, LAMP observes the water ice absorption edge at 165 nm within PSRs. Although this is a spectral signature, the low levels of illumination only allow binning the spectrum into broad wavelength ranges. Gladstone et al. (2012) and Hayne et al. (2015) present maps using this FUV spectral signature. The spectral properties of lunar regolith mixed with water and ice are not well studied in the UV. Although these measurements are consistent with the presence of water frost, they are better suited for supporting other observations. Similarly, 1064-nm surface reflectance measurements from LOLA indicate systematically brighter surfaces within PSRs, further bolstering evidence for surface frost (Lucey et al., 2014).

Neutron spectroscopy is sensitive to the presence of H, although it cannot distinguish among various chemical forms. Neutron data from LPNS and LRO LEND both show a depression in neutron flux at high latitudes that is associated with an enhancement in H. Other compositional differences, topography, and thermal processes affect the flux of neutrons. However H presents the strongest modulation of neutron flux in the epi-thermal energy range. Neutron spectra are consistent with an overall enhancement of H-bearing material at high latitudes (Feldman et al., 1998), which supports an inferred thermal mechanism for retaining the material. Thus thermal studies offer an important constraint in that they provide information about the regions where certain volatiles are stable against loss. The Diviner temperature measurements provide data for all times of day and seasons (Paige et al., 2010) and these measured temperatures are consistent with the sequestration of hydrogen in colder locations near the lunar poles.

Additional measurements that would improve the understanding of the composition of

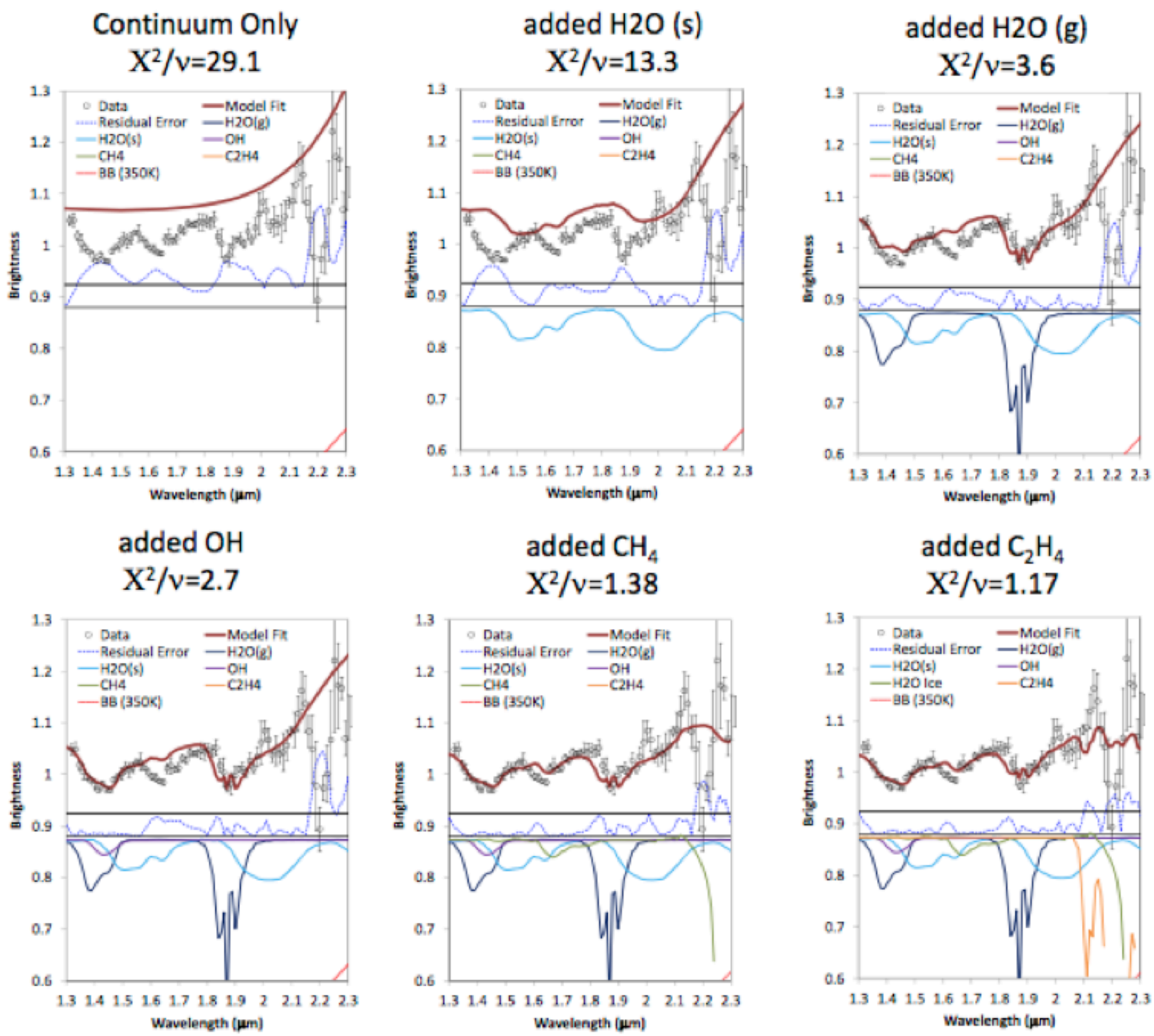

Figure 1. (Colaprete et al. 2010) Reflectance spectra of plume material lofted into sunlight by the LCROSS impact. Sequential model fits adding H_2O (in solid and vapor phases), OH, CH_4, and C_2H_4 to a continuum spectrum reproduce the observation.

volatiles in the PSRs include active spectroscopy from orbit, which would provide spectral confirmation of the composition of the surface. In situ instrumentation on the surface using mass spectroscopy, nuclear spectroscopy, LIBS, TLS, RAMAN, gas chromatography, or active optical spectroscopy would determine the composition of local samples.

B. DISTRIBUTION

The distribution of water in lunar polar regions is heterogeneous on many scales down to the limit of existing spatial resolution. Neutron data indicate that H is enhanced at high latitudes, both inside and outside of PSRs. These measurements are sensitive to both the depth and lateral distribution. Surface reflectance data, which lack information about depth, indicate that not all PSRs have uniform albedo within the crater, consistent with a diversity of surface processes.

Both radar and neutron data are sensitive to the presence of volatiles within the top meter of regolith. Analyzing the flux of neutrons in multiple energy ranges provides information about the average depth distribution. One location, Shackleton crater, has high fast neutron flux consistent with H on the surface (Miller et al., 2014). Lawrence et al. (2011) found that although a depression in epithermal neutrons is the expected signature when H is buried, there may actually be excess epithermal neutrons if that H resides near the surface. Therefore, the differences in epithermal neutron flux from crater to crater may reflect differences in the depth of the H or may be caused by different abundances of H. In Shoemaker Crater, LAMP data are consistent with small amounts of frost on the surface (Figure 2), but LEND data support large amounts of H (Figure 3). In Haworth Crater, by contrast, LEND data show little neutron suppression, which can be interpreted as low H content. This crater, however, has a strong signature of surface frost using LAMP data. Coupling the two datasets suggests that surface frost in Haworth may obscure the neutron depression signature; whereas the H –bearing material is at greater depth in Shoemaker. In contrast, Faustini Crater appears to have lower abundance of ice both at the surface and at depth.

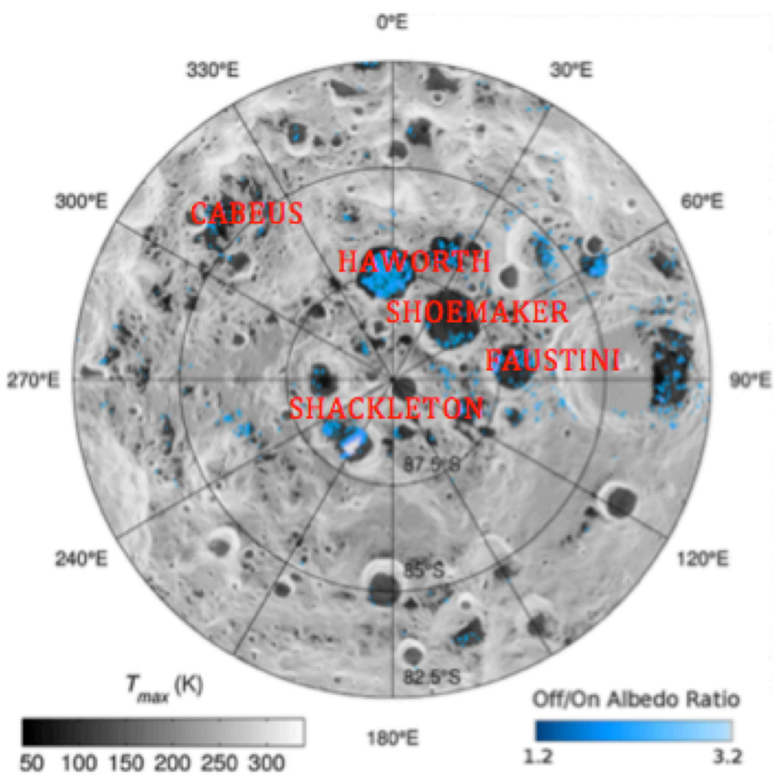

Figure 2. (Hayne et al. 2015) Map of the lunar south polar region showing the maximum temperature (gray scale) from LRO Diviner measurements and the surface frost (blue scale) from LRO LAMP measurements of the 165-nm feature.

Within an individual PSR, there is

still heterogeneity in measured water distributions. Laser reflectivity experiments demonstrate a correlation between lunar albedo at 1064 nm and low temperatures. LOLA data (Lucey et al., 2014) indicate higher reflectivity on poleward facing slopes than on equatorward facing slopes. LAMP and LEND data also exhibit differences on poleward facing slopes that require further investigation. The abundance of water inferred from the LCROSS impact, 5%, was greater than the abundance of the surrounding region, 0.5% inferred from neutrons (Sanin et al., 2016), indicating the impact was into a subregion that was relatively ice-rich. Alternatively, the high abundance of water could have originated at depth below the ~1 m depth probed by neutron spectroscopy. The crater formed by the LCROSS impact is expected to have excavated to a depth of 2-3 m. Indeed a temperature gradient is expected with depth that might influence the depth profile of trapped water ice. However in the PSR of Cabeus Crater, the temperature is so cold that ice is expected to be immobile at all depths given the present obliquity of the Moon.

Elsewhere, where warmer temperatures exist, a thermally stable zone may exist at depth even if ice is not stable for long times on the surface. Additional removal processes may be active at the extreme surface, including photolysis by ultraviolet light, impact vaporization by meteoroids, and sputtering by solar wind. For these reasons, it is expected that subsurface access may be either beneficial or required for ISRU of lunar polar water ice deposits.

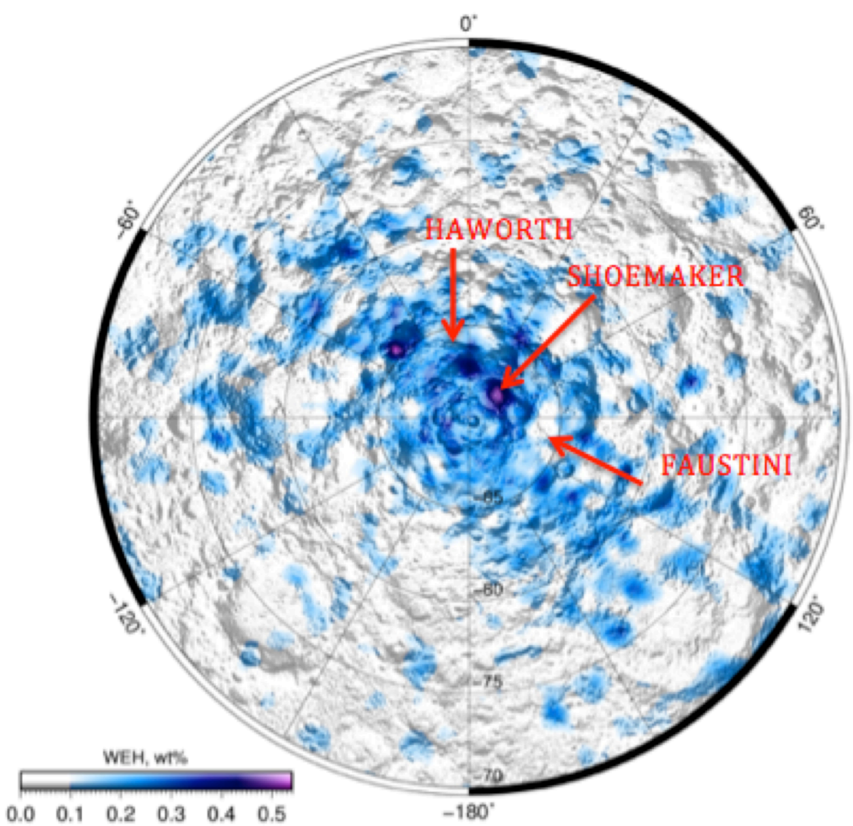

Figure 3. (Sanin et al., submitted) Hydrogen content in the top meter of regolith in the south polar region measured by the suppression of neutrons in the epi-thermal energy range by LRO LEND. The values are converted to the equivalent amount of water that bears that hydrogen. Heterogeneity would produce local enhancements and depressions around these average values.

Removal processes may also redistribute water ice laterally and produce lateral heterogeneity. However, they offer a potential for sampling the contents of PSRs from adjacent regions that are not in permanent shadow. Future reconnaissance could perch on the edge of volatile-rich PSR and monitor the influx and outflux of volatile material from impacts (Farrell et al., 2015).

Because the heterogeneity persists down to the spatial resolution of existing measurements, new measurements with better spatial resolution would improve the understanding of the lateral distribution of volatiles.

C. ABUNDANCE

Measurement of the abundance conflates the heterogeneous distribution of water ice and the spatial resolution of the data. Thus these measurements represent averages on size scales > 1 km.

Neutron spectroscopy provides the best integrated measure of the abundance of volatiles in lunar polar regions, albeit with ambiguity regarding the actual chemical composition. LPNS data are consistent with 1.5 ± 0.8% water-equivalent hydrogen distributed within the top 1 m of regolith in the polar regions if it is confined to the area in PSRs (Feldman et al., 2001). In PSRs within 10° of the pole and 1 m of the surface, this integrates to a total water abundance on the order of 10^{11} kg of water (Eke et al., 2009). More recent LEND data yield similar values on average (Sanin et al., submitted).

The measurements sensitive to the abundance on the extreme surface are consistent with concentrations < 2-3% in all PSRs, and < 1 % in most PSRs. However, there are many assumptions behind these numbers and the systematic uncertainties are high. Because the surface values are not drastically different from the volume-integrated values, the volume-integrated material is adequate to represent the overall abundance.

The LCROSS impact revealed a relatively high local abundance of water ice. However, the estimated 5% abundance of water assumes that the abundance in the plume is representative of the abundance in the regolith. This is a good assumption for slow ejecta that are mechanically displaced through the impact. However, the vaporized fraction may not be stoichiometric, as was inferred through analysis of the LAMP observations of the plume (Hurley et al., 2012). Therefore, 5% abundance of water can be taken as an upper limit. Together with the lower limit from the neutron data, there are likely locations in the PSRs with abundances of a few percent water ice by weight.

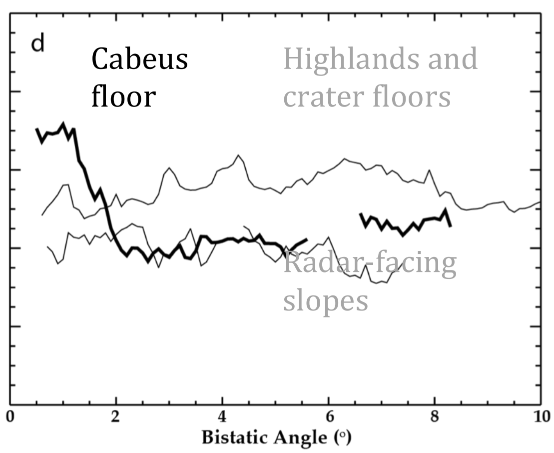

Figure 4. (Patterson et al. submitted) Circular polarization ratio from Mini-RF from within Cabeus crater (black line) has peak at low phase angle, consistent with water ice. This is the only data consistent with ice blocks on the Moon presently in hand.

D. PHYSICAL FORM

Presently, there is very little known about the physical form of water ice in lunar polar regions. Radar data would reveal if coherent, pure ice layers exist through the properties of the coherent backscatter. Unlike at the planet Mercury, radar evidence is not consistent with widespread, ice layers with thickness > 10 cm on the Moon. On the illuminated Moon, if the inside of the crater has high CPR, the outside of the crater does as well implying blocks of rocky ejecta, not ice for those craters. However, two observations possibly support the presence of coherent ice blocks. One is the observation that the interiors of some polar craters have anomalously high CPR (Spudis et al., 2013) without an accompanying high CPR signature outside of the crater. This may indicate a subsequent deposition of ice those craters in PSRs. However, this is controversial and has not been confirmed by an independent technique. Secondly, bi-static observations using Mini-RF have revealed a phase effect in the CPR in Cabeus Crater (Figure 4) that is also more consistent with blocky ice than with rock (Patterson et al., submitted). Therefore, there may be isolated regions both inside and outside of PSRs with coherent ice blocks, but more measurements are needed.

The LCROSS experiment also sheds some light on the physical form of water in PSRs. The spectra were modeled using a combination of ice and water vapor, indicating that at least some of the water, if not all of it, is stored as ice in Cabeus. Additional studies of the time evolution of the plume indicate a shift in color that is attributed to a change in the size of the dust grains over time (Heldmann et al., 2015). The data are consistent with the sublimation of ice from the grains over time. However, LAMP observed larger quantities of H_2 in the plume than can be produced by photodissociation of water. This implies that at least some of the H observed by neutrons is not in the form of water ice.

However, the lack of pervasive signature in radar is consistent with ice filling the pore space, adsorbed layers, hydrated minerals, or ice blocks < 10 cm in scale. It is unlikely that “skating rinks” of ice exist on the Moon.

III. Next Steps

Many of the next steps to facilitate ISRU of lunar polar water are summarized in the 2014 Lunar Exploration Analysis Group (LEAG) Volatiles Strategic Action Team (VSAT) report. We concur with that assessment. Multiple missions are being planned that, if successful, would enhance the understanding of the composition, distribution, and abundance of water in lunar polar regions including the rover Resource Prospector and lunar cubesats LunaH-Map, Lunar IceCube, and Lunar Flashlight. A multi-faceted approach is necessary to effectively characterize the resource. Ground truth is essential to provide in situ confirmation of the composition and abundance. Subsurface access would resolve the depth distribution. Observations both inside and outside of PSRs with lateral spatial resolution spanning 1 m – 100 m distance scales are most relevant. Monitoring the present day variability in the reservoir would provide data on durability and potential for renewal of water on timescales relevant for human exploitation. Further, scientific understanding via laboratory experiments, theoretical work, and modeling would facilitate evaluating and planning ISRU. Modeling that relates the existing water to its sources, the timing of its emplacement, and the processes maintaining and redistributing volatiles will enable us to integrate diverse and ancillary data to predict locations with enhanced water content. Laboratory experiments are crucial for interpreting remote sensing data, understanding the interactions between volatiles and regolith, and illuminating the geotechnical properties of materials.

Table 2. Results, data sources, interpretation

Result	Source	Evaluation	Reference
H_2O ice and vapor identified in LCROSS plume	LCROSS VIR	Accepted: Spectral fits are significantly improved by including these species; Quantities in plume are well-constrained; Conversion to abundance in regolith is less constrained	Colaprete et al. Science 2010; Heldmann et al. Icarus 2015
H_2, CO, Hg, Na, OH, others spectrally identified in PSRs via LCROSS impact	LRO LAMP; Earth-based telescopes; LCROSS VSP; LCROSS VIR; LCROSS NIR	Mostly accepted: Spectral signatures are unambiguous identifiers of species; Quantities in plume are well-constrained; Conversion to abundance in regolith is less constrained	Killen et al. GRL 2010; Gladstone et al. Science 2010; Hurley et al. JGR 2012; Colaprete et al. Science 2010; Schultz et al. Science 2010; etc.
Water frost spectrally identified in PSRs	LRO LAMP	Accepted but not conclusive: Spectral detection of 165 nm absorption feature of water frost uses low-level illumination source and broad wavelength bins.	Gladstone et al. JGR 2012; Hayne et al. Icarus 2015
H (polar)	LRO LEND; LPNS	Accepted: Constrains mass fraction of regolith in hydrogen; Although hydrogen could be in form of water, this technique does not constrain it; Provides some insight into the depth distribution as technique is sensitive to top 1 m of regolith	McClanahan et al. Icarus 2015; Boynton et al. 2012; Mitrofanov et al. 2012; Sanin et al. 2012; Mitrofanov et al. Science 2010; Lawrence et al. JGR 2006; Feldman et al. 2000; Feldman et al. Science 1998
Hydrogen distribution is heterogeneous from within and between PSRs	LRO LEND; LPNS	Accepted: Heterogeneity observed down to the scale size of the measurements; The applicable scale size of the neutron measurements is debated	Eke et al. Icarus 2009; Elphic et al. GRL 2007
Water is buried below dry regolith	LPNS; LCROSS	Consistent but not conclusive: Neutron leakage models give energy spectra consistent with observations by assuming a dry layer at the surface over a wet layer; Hydrogen not necessarily in form of water ice	Lawrence et al. JGR 2006; Feldman et al. JGR 2001

Hydrogen may be closer to surface at Shackleton crater	LPNS	Consistent but not conclusive: Fast neutron signature is statistically significant in Shackleton	Miller et al. Icarus 2014
Water frost has heterogeneous distribution within PSRs	LRO LOLA; LRO LAMP	Accepted but not conclusive: Heterogeneity observed down to the scale size of the measurements; Correlation between temperature and albedo measurements strengthens thermal argument for albedo signature, consistent with water frost.	Lucey et al. JGR 2014; Hayne et al. Icarus 2015
CPR in radar data is consistent with basketball-sized ice blocks in PSRs	LRO Mini-RF, Chandrayaan-1 Mini-SAR; Clementine	Speculative: High CPR could also indicate blocky material from fresh impacts; Stronger signature observed at Mercury is unexplained relative to Moon;	Spudis et al. JGR 2013; Simpson and Tyler JGR 1999; Nozette et al. JGR, 2001
Bi-static radar observation in Cabeus is consistent with coherent, but thin ice layer	LRO Mini-RF	Preliminary: Small sample size; Multiple possible causes of observed signal	Patterson et al. Icarus submitted
Proton albedo consistent with the presence of hydrogen in upper 10 cm of regolith	LRO CRaTER	Preliminary: Small sample size; Interpretation is model dependent	Schwadron et al. Icarus 2016
Mercury PSRs have strong signals consistent with ice in radar; neutrons; albedo in scattered light; 1064 nm albedo	MESSENGER MLA, MASCS, NS; Arecibo	Accepted: High radar CPR consistent with thick, pervasive water ice deposits; Bright albedo features correlate to thermal stability of water ice on the surface; Dark albedo features correlate to thermal stability of ice in the subsurface; Neutron data relate high hydrogen content to polar regions	Paige et al. 2013; Lawrence et al. 2013; Chabot et al. 2013

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